

Research Article

Outage Analysis of Cooperative Transmission with Energy Harvesting Relay: Time Switching vs Power Splitting

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Abstract Recently, energy harvesting (EH) has emerged as a promising way to realize green communications. In this paper, we investigate the multiuser transmission network with an EH cooperative relay, where a source transmits independent information to multiple destinations with the help of an energy constrained relay. The relay can harvest energy from the radio frequency (RF) signals transmitted from the source, and it helps the multiuser transmission only by consuming the harvested energy. By adopting the time switching and the power-splitting relay receiver architectures, we firstly propose two protocols, the time-switching cooperative multiuser transmission (TSCMT) protocol and the power-splitting cooperative multiuser transmission (PSCMT) protocol, to enable the simultaneous information processing and EH at the relay for the system. To evaluate the system performance, we theoretically analyze the system outage probability for the two proposed protocols, and then derive explicit expressions for each of them, respectively. Moreover, we also discuss the effects of system configuration parameters, such as the source power and relay location on the system performance. Numerical results are provided to demonstrate the accuracy of our analytical results and reveal that compared with traditional non-cooperative scheme, our proposed protocols are green solutions to offer reliable communication and lower system outage probability without consuming additional energy. In particular, for the same transmit power at the source, the PSCMT protocol is superior to the TSCMT protocol to obtain lower system outage probability.

key words: Energy harvesting (EH), outage probability, amplify-and-forward (AF), cooperative communication

1. Introduction

Recently, energy harvesting (EH) has emerged as a promising approach to overcome the limited energy budget of wireless networks, especially for wireless sensor networks or other networks with fixed energy supplies [1]-[7]. Conventional EH techniques gather energy from surrounding natural environment, for example, solar, wind, pressure, thermoelectric effects, etc. [1]-[4]. However, the energy obtained from physical phenomena is not always available and not easily controlled [5]. To this end, one promising solution is to harvest energy from the ambient radio-frequency (RF) signals [5]-[7], [14]-[20].

Cooperative communication, a technique initially proposed to offer high capacity and reliability by exploiting spatial diversity [8], [9], [10] has been proved to be capable of improving the energy efficiency of networks [11]-[13]. More recently, efforts have been made to apply EH to cooperative wireless networks to improve the performance of energy-constrained systems. As most devices used in wire-

less network are surrounded by RF signals (e.g., Wi-Fi signals or cellular signals), and these RF signals can carry energy and information simultaneously. Thus much attention has been paid to EH from RF signals [14]-[20], which is ideal for cooperative communication networks, because the transmissions of cooperation nodes can be powered by the energy harvested from the incoming signals rather than external energy supply. Specifically, in [14], a one-way transmission among one source-destination pair was studied via an EH cooperative relay, where the achievable throughput at the destination was derived. In [15], the author investigated the system achievable throughput and ergodic capacity of a decode-and-forward (DF) two-hop relaying network with an EH relay. In [16], an amplify-and-forward (AF) two-hop transmission with the help of an EH relay was considered, where the maximal achievable information of the system were analyzed. In [17], the outage performance analysis and optimization were investigated for a DF two-way relay network with an EH relay. In [18], a cooperative uplink transmission among two users with downlink energy transfer was considered, where the system outage performance was studied. In [19], the outage probability was characterized for users in a cooperative network where multiple source-destination pairs communicated with each other via an EH relay. In [20], different power allocation strategies were proposed and evaluated for the system where multiple source-destination pairs communicated with the help of a common EH relay. However, to the best of our knowledge, there has been no work investigating the multiuser transmission via an EH cooperative relay.

In this paper, we focus on the multiuser transmission network, where a source transmits independent information to multiple destinations with the help of an energy-constrained relay. The multiuser transmission network is a universal model. For example, in cellular networks, several mobile users download files from a common base station simultaneously. Moreover, if the multiuser transmission could be assisted by a wireless cooperative relay, the reliability of system can be greatly improved [21], [22]. In particular, in [21], a network coding-aware cooperative relaying scheme was presented for downlink cellular networks, where two relay nodes were used to assist the transmissions for two users. In [22], an opportunistic network coding relaying cooperative scheme was proposed for a cellular downlink transmission network, where the outage performance was analyzed.

However, all the above work did not consider EH at the relay, that is to say, the cooperative relay has to consume

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its own energy to assist the multiuser transmission, whereas sometimes the relay is unwilling to help due to the selfish nature or the lack of energy supply. In our work, we also focus on the multiuser transmission network, where a cooperative relay is applied to assist the multiuser transmission. Compared with previous work [19], [21], [22], some differences of our work are deserved to be stressed as follows. Firstly, we apply EH to the cooperative relay. The EH relay can harvest energy from the RF signals it received from the source, and uses all the harvested energy to cooperate the information transfer. Secondly, in [19], the authors considered a cooperative network with multiple source-destination pairs communicating with each other via an EH DF relay, and the impact of spatial randomness of user locations on the system outage probability was studied, whereas in this work, we aim to investigate the performance gain that the EH AF relay brings compared with the traditional non-cooperative transmission, and focus on the effect of relay position on the system outage probability.

Our main contributions can be summarized as follows. Firstly, two transmission protocols, i.e., time switching-based cooperative multiuser transmission (TSCMT) protocol and power splitting-based cooperative multiuser transmission (PSCMT) protocol, are proposed by applying the practically realizable receiver architectures in [7] to enable the simultaneous information processing and EH at the AF relay. Secondly, for each proposed protocol, we theoretically analyze the system outage performance and derive an explicit expression for the system outage probability. As the outage probability is one of the most important performance metrics for the cooperative networks, there have been lots of works investigating the outage performance in cooperative systems [19], [20], [23]-[26]. Thirdly, based on the analytical outage probability, we discuss the effects of system configuration parameters, such as the source power and relay location on the system performance. Extensive numerical results show that the two proposed protocols outperform the traditional non-cooperative scheme in term of outage probability. Moreover, due to the fact that the energy used by the relay is harvested from the RF signals in communication networks, our proposed protocols can improve the system outage performance without consuming extra energy.

The rest of the paper is organized as follows. Section 1 describes the system model. Section 3 and Section 4 present the proposed TSCMT and PSCMT protocols, and analyze the system outage performance for each protocol, respectively. In Section 5, we provide numerical results. Finally, the conclusion is followed in Section 6.

2. System Model

Consider a multiuser cooperative transmission network composed of a source S, two destinations (referred to as D_1 and D_2) and an energy-constrained relay R, as shown in Fig. 1. We assume that S has its own internal energy source and wants to transfer independent information x_1 and x_2 to D_1 and D_2 with the help of R, respectively. The energy con-

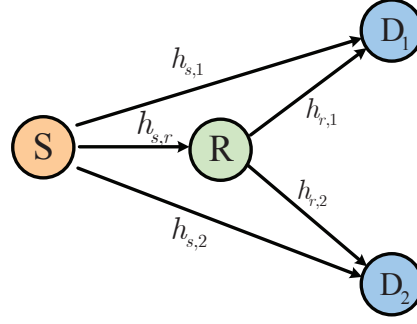


Fig. 1 System model and parameters.

strained R relies on external charging, thus it harvests energy from the received RF signals transmitted from S, and use all the harvested energy to help the transmissions from S to D_1 and D_2 . We also assume that all the terminals have a single antenna and operate in a half-duplex mode.

Let $h_{s,r}$, $h_{s,1}$, $h_{s,2}$, $h_{r,1}$ and $h_{r,2}$ denote the complex channel coefficient of S to R channel, S to D_1 channel, S to D_2 channel, R to D_1 channel and R to D_2 channel respectively. We assume that all the channels are quasi-block fading channel, following Rayleigh fading. Also, the channels are modeled as follows: $h_{s,r} \sim \mathcal{CN}(0, \Omega_{s,r})$, $h_{s,1} \sim \mathcal{CN}(0, \Omega_{s,1})$, $h_{s,2} \sim \mathcal{CN}(0, \Omega_{s,2})$, $h_{r,1} \sim \mathcal{CN}(0, \Omega_{r,1})$, and $h_{r,2} \sim \mathcal{CN}(0, \Omega_{r,2})$. Specifically, let $d_{s,r}$, $d_{s,1}$, $d_{s,2}$, $d_{r,1}$ and $d_{r,2}$ denote the distance from S to R, from S to D_1 , from S to D_2 , from R to D_1 , and from R to D_2 , respectively. As a result, $\Omega_{s,r} = d_{s,r}^{-m}$, $\Omega_{s,1} = d_{s,1}^{-m}$, $\Omega_{s,2} = d_{s,2}^{-m}$, $\Omega_{r,1} = d_{r,1}^{-m}$ and $\Omega_{r,2} = d_{r,2}^{-m}$, where m denotes the path loss exponent.

With such a system model and assumptions mentioned above, we will describe our proposed two cooperative protocols in Section 3 and Section 4.

3. Time Switching-based Cooperative Multiuser Transmission (TSCMT) Protocol

In this section, we consider the time switching receiver architecture proposed in [7]. We shall first detail the proposed cooperative protocol, and then analyze the system outage performance for it[†].

3.1 Protocol Description

Fig. 2 depicts the transmission process and key parameters in the proposed TSCMT protocol. For a time period T , let $0 \leq \rho \leq 1$ denote the time assignment factor, such that ρT

[†]Energy harvesting from RF signal, which is also known as simultaneous wireless information and energy transfer (SWIET) was first proposed in 2008 [6]. In the year of 2012, the authors in [7] first proposed two practically realizable receiver architecture designs, in which EH and information detection could be operated in time switching (TS) or power splitting (PS) patterns. So far, these two receiver schemes have been widely adopted and used in various wireless systems [14]-[18]. Considering that the two receiver designs are easy to be implemented in practical systems, we design the TSCMT and PSCMT protocols on the basis of TS and PS receiver architecture respectively.

Energy Harvesting		Information Transmission		
$\rho T/2$	$\rho T/2$	$(1-\rho)T/3$	$(1-\rho)T/3$	$(1-\rho)T/3$
EH at R from S	EH at R from S	S Broadcast x_1	S Broadcast x_2	R Broadcast x_R with P_r

Fig. 2 Key parameters in the proposed TSCMT protocol.

part is assigned for R to harvest energy from S, where it is equally divided into two time durations. Each $\rho T/2$ duration is assigned for R to harvest energy from S during the period when S broadcasts x_i ($i = 1, 2$) with power P_i . The remaining part $(1-\rho)T$ is used for the information transmission, which is equally divided into three parts. During the first two $(1-\rho)T/3$ durations, S broadcasts information x_i with power P_i , both D_1 , D_2 and R can receive the signal. In the third time duration of $(1-\rho)T/3$, R first combines the two signals it received, and then uses all the energy harvested from S to broadcast the combined signal x_R . In the following subsection, we will analyze the system outage performance for the TSCMT protocol.

3.2 Outage Probability Analysis for the TSCMT Protocol

In this section, we will analyze the expression of the outage probability for the transmission from S to D_1 . Note that, the transmission from S to D_2 has the similar outage performance due to the symmetry of the system.

As illustrated in Fig. 2, S broadcasts its information x_i^\dagger with power P_i , both D_1 , D_2 and R can receive it. The received signals $y_{s,i}$ at D_i , and the received signals $r_{s,j}$ at D_j ($j = 1, 2$ and $j \neq i$) are given as follows, respectively:

$$y_{s,i} = \sqrt{P_i}h_{s,i}x_i + n_{s,i}, \quad (1)$$

$$r_{s,j} = \sqrt{P_i}h_{s,j}x_i + v_{s,j}, \quad (2)$$

where $n_{s,i}$ and $v_{s,j}$ are the additive white Gaussian noise (AWGN) at D_i and D_j with $n_{s,i} \sim \mathcal{CN}(0, 1)$ and $v_{s,j} \sim \mathcal{CN}(0, 1)$. Note that, $y_{s,i}$ is the desired signal of D_i , whereas $r_{s,j}$ is the signal that can help D_j decode x_i from the mixed signal transmitted by R in the third phase.

After the processing of the relay receiver, the sampled baseband signal at R is given as follows

$$y_{r,i} = \sqrt{P_i}h_{s,r}x_i + n_{r,i}, \quad (3)$$

where $n_{r,i}$ is the AWGN at R with $n_{r,i} \sim \mathcal{CN}(0, 1)$. The energy that R harvests from S is given as follows [5], [14]-[18]

$$E_i = \eta P_i |h_{s,r}|^2 \cdot \frac{\rho T}{2}, \quad (4)$$

where $0 \leq \rho \leq 1$ denotes the time assignment factor, and

[†]Both x_1 and x_2 have unit average power

$0 < \eta \leq 1$ denotes the energy conversion efficiency.

After the first two transmissions from S, the relay has harvested total $E_1 + E_2$ energy from S. So, the transmit power at R in the following phase is given by

$$P_r = \frac{E_1 + E_2}{(1-\rho)T/3} = \frac{3\rho}{2(1-\rho)} \cdot \eta(P_1 + P_2)|h_{s,r}|^2. \quad (5)$$

R first combines the two signals $y_{r,1}$ and $y_{r,2}$ as x_R [23], [27], and uses P_r to broadcast the combined signal x_R . Specifically, x_R is given as follows

$$x_R = \xi_1 y_{r,1} + \xi_2 y_{r,2}, \quad (6)$$

where ξ_i ($i = 1, 2$) denotes how R combines $y_{r,1}$ and $y_{r,2}$, and is selected as follows:

$$\xi_i = \sqrt{\frac{\theta_i}{P_i|h_{s,r}|^2 + 1}} \approx \sqrt{\frac{\theta_i}{P_i|h_{s,r}|^2}}, \quad (7)$$

where $0 < \theta_i < 1$ ($i = 1, 2$), and $\theta_1 + \theta_2 = 1$. The approximation in (7) is widely adopted in similar articles [?], [27]. Note that, x_R always has unit power irrespective of θ_i .

After combining the two signals $y_{r,1}$ and $y_{r,2}$, R broadcasts x_R with power P_r , and the signals received by D_1 and D_2 are given as follows:

$$y_{d,i} = \sqrt{P_r}h_{r,i}x_R + n_{d,i}, \quad (8)$$

where $n_{d,i}$ is the AWGN at D_i ($i = 1, 2$) with $n_{d,i} \sim \mathcal{CN}(0, 1)$. Because D_1 (D_2) can decode x_2 (x_1) from (2), it can remove x_2 (x_1) from $n_{d,1}$ ($n_{d,2}$). Thus, D_1 can obtain the interference-free signal as follows:

$$\begin{aligned} \tilde{y}_{d,1} = & \sqrt{P_r}h_{r,1}\xi_1 \sqrt{P_1}h_{s,r}x_1 + \sqrt{P_r}h_{r,1}\xi_2 n_{r,2} \\ & + \sqrt{P_r}h_{r,1}\xi_1 n_{r,1} + n_{d,1}. \end{aligned} \quad (9)$$

Then, submitting P_r in (5), and using the approximation in (7), the instantaneous SNR γ_1 of the signal $\tilde{y}_{d,1}$ is given as follows

$$\gamma_1 = \frac{\frac{3\rho}{2(1-\rho)} \cdot \eta(P_1 + P_2)\theta_1|h_{s,r}|^2|h_{r,1}|^2}{\frac{3\rho}{2(1-\rho)} \cdot \eta(P_1 + P_2)\left(\frac{\theta_1}{P_1} + \frac{\theta_2}{P_2}\right)|h_{r,1}|^2 + 1}. \quad (10)$$

By receiving two copies of x_1 , D_1 performs the maximal ratio combining (MRC). MRC is a method of diversity combining, in which the different copies of the same transmitted signal are added together to enhance the total received SNR at the destination [24], [27]. With the instantaneous SNR of the direct link from S to D_1 which is denoted by $\gamma_0 = P_1|h_{s,1}|^2$, we can obtain the mutual information of the transmission from S to D_1 as follows

$$I_1 = \frac{2(1-\rho)}{3} \log(1 + \gamma_0 + \gamma_1). \quad (11)$$

As is known, the outage probability represents the probability which the target transmission rate is not supported due to the variations of channels. It is usually used

Phase 1	Phase 2	Phase 3
$T/3$	$T/3$	$T/3$
EH at R from S ($\alpha_1 P_1 h_{s,r}^2$)	EH at R from S ($\alpha_2 P_2 h_{s,r}^2$)	R Broadcast x_R with P_r
S Broadcast x_1 ($(1-\alpha_1)P_1 h_{s,r}^2$)	S Broadcast x_2 ($(1-\alpha_2)P_2 h_{s,r}^2$)	

Fig. 3 Key parameters in the proposed PSCMT protocol.

to evaluate the performance over fading channels [23]- [25]. In our work, an outage occur when the mutual information in (11) falls below the targeted rate R_t . Thus, the outage probability can be calculated as

$$P_{\text{out}}^{(\text{TS})} = \Pr(I_1 < R_t) \\ = \Pr\left(\frac{2(1-\rho)}{3} \log(1 + \gamma_0 + \gamma_1) < R_t\right). \quad (12)$$

Theorem 1: Given a target transmission rate R_t , the outage probability of the TSCMT protocol for the multiuser cooperative transmission system with an EH relay is given as follows

$$P_{\text{out}}^{(\text{TS})} = 1 - \exp\left(-\frac{R_0}{P_1 \Omega_{s,1}}\right) + \sum_{l=1}^{\infty} \frac{\exp\left(-\frac{R_0 b}{a \Omega_{s,r}}\right) c^{l+1}}{P_1 \Omega_{s,1} (a \Omega_{s,r} \Omega_{r,1})^{l+1} l! (l+1)!} \\ \times \left\{ \left(\ln \frac{c}{a \Omega_{s,r} \Omega_{r,1}} + 2C - \sum_{k=1}^l \frac{1}{k} - \sum_{k=1}^{l+1} \frac{1}{k} \right) \right. \\ \times \left(\frac{1}{P_1 \Omega_{s,1}} - \frac{b}{a \Omega_{s,r}} \right)^{-l-2} \times \gamma\left(l+2, \frac{R_0}{P_1 \Omega_{s,1}} - \frac{b R_0}{a \Omega_{s,r}}\right) \\ \left. + H_l \right\} + \frac{\exp\left(-\frac{R_0}{P_1 \Omega_{s,1}}\right) c}{a \Omega_{s,r} \Omega_{r,1} P_1 \Omega_{s,1}} \left\{ \left(\ln \frac{c}{a \Omega_{s,r} \Omega_{r,1}} + 2C \right) \right. \\ \times \left(\frac{1}{P_1 \Omega_{s,1}} - \frac{b}{a \Omega_{s,r}} \right)^{-2} \times \gamma\left(2, \frac{R_0}{P_1 \Omega_{s,1}} - \frac{b R_0}{a \Omega_{s,r}}\right) + H_0 \left\} \right. \\ \left. - \frac{a \Omega_{s,r}}{a \Omega_{s,r} - b P_1 \Omega_{s,1}} \left(\exp\left(-\frac{R_0}{P_1 \Omega_{s,1}}\right) - \exp\left(-\frac{R_0 b}{a \Omega_{s,r}}\right) \right) \right\}. \quad (13)$$

where $\gamma(\cdot)$ denotes the incomplete gamma function, $R_0 = 2^{\frac{1.5 R_t}{1-\rho}} - 1$, $a = \frac{3}{2} \rho (1-\rho)^{-1} \eta (P_1 + P_2) \theta_1$, $b = a P_2^{-1} + a \theta_1 P_1^{-1} \theta_2^{-1}$, $c = 1$, and $C \approx 0.5772$ is Euler's constant. Here we have

$$\mathcal{H}_l = \int_0^{R_0} \exp\left(-\frac{(a \Omega_{s,r} - b P_1 \Omega_{s,1}) \tau}{a P_1 \Omega_{s,1} \Omega_{s,r}}\right) \tau^{l+1} \ln \tau d\tau. \quad (14)$$

Proof: See Appendix A. \square

4. Power Splitting-based Cooperative Multiuser Transmission (PSCMT) Protocol

In this section, by considering the power splitting receiver

architecture, we shall first detail the proposed PSCMT protocol, and then analyze the system outage performance for it.

4.1 Protocol Description

Fig. 3 illustrates the transmission process and key parameters in the proposed power splitting-based cooperative multiuser transmission (PSCMT) protocol. As shown in the figure, the transmission is accomplished through three phases, and each phase lasts for a time duration of $T/3$. During the i -th ($i = 1, 2$) phase, S broadcasts its information x_i with power P_i , both D_1 , D_2 and R can receive the signal. The part $(1 - \alpha_i)P_i h_{s,r}^2$ is used for the information transmission from S to R, where $0 \leq \alpha_i \leq 1$ denotes the power splitting factor, and the other part $\alpha_i P_i h_{s,r}^2$ is used for energy harvesting at R. In the third phase, the relay first combines the two signals it received in the first two phases, and then uses the energy harvested from S to broadcast the combined signal x_R in a time duration of $T/3$.

4.2 Outage Probability Analysis for the PSCMT Protocol

As illustrated in Fig. 3, during the i -th ($i = 1, 2$) phase, S broadcasts its information x_i with power P_i . The received signals $y_{s,i}$ at D_i , and the received signals $r_{s,j}$ at D_j ($j = 1, 2$ and $j \neq i$) are given in (1) and (2), respectively.

At the end of the i -th phase, after the processing of the relay receiver, the sampled baseband signal at R is given as follows

$$y_{r,i} = \sqrt{(1 - \alpha_i)P_i} h_{s,r} x_i + n_{r,i}, \quad (15)$$

where $0 \leq \alpha_i \leq 1$ ($i = 1, 2$) denotes the power splitting factor, and $n_{r,i}$ is defined below (3). The energy that R harvests from S is given by

$$E_i = \eta P_i \alpha_i |h_{s,r}|^2 \cdot \frac{T}{3}, \quad (16)$$

where η is defined below (4).

After the first two phases, the relay has harvested total $E_1 + E_2$ energy from S. So, the transmit power at R in the third phase is given by

$$P_r = \frac{E_1 + E_2}{T/3} = \eta (\alpha_1 P_1 + \alpha_2 P_2) |h_{s,r}|^2. \quad (17)$$

During the third phase, R first combines the two signals x_1 and x_2 as x_R , which is given in (6), and uses the power P_r to broadcast the combined signal x_R .

At the end of the third phase, the signals received by D_1 and D_2 are given in (8). Similar to the process in the TSCMT protocol described in subsection 3.2, after removing the interference signal $y_{d,2}$, D_1 can obtain the interference-free signal as follows:

$$\tilde{y}_{d,1} = \sqrt{P_r} h_{r,1} \xi_1 \sqrt{(1 - \alpha_1)P_1} h_{s,r} x_1 + \sqrt{P_r} h_{r,1} \xi_2 n_{r,2} \\ + \sqrt{P_r} h_{r,1} \xi_1 n_{r,1} + n_{d,1}. \quad (18)$$

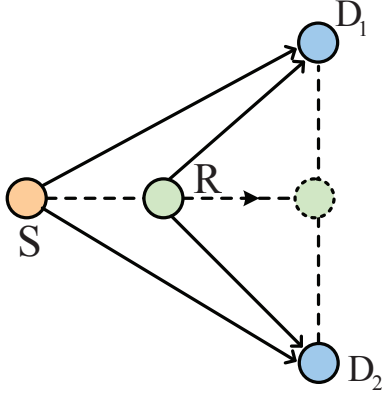


Fig. 4 Illustration of the relay position.

Submitting P_r from (17) into (18), and using the approximation in (7), the instantaneous SNR γ_1 of the signal $\tilde{y}_{d,1}$ is given as follows

$$\gamma_1 = \frac{\eta(\alpha_1 P_1 + \alpha_2 P_2) \theta_1 |h_{s,r}|^2 |h_{r,1}|^2}{\eta(\alpha_1 P_1 + \alpha_2 P_2) |h_{r,1}|^2 \left(\frac{\theta_1}{P_1(1-\alpha_1)} + \frac{\theta_2}{P_2(1-\alpha_2)} \right) + 1}. \quad (19)$$

Similar to the TSCMT protocol, D_1 performs the maximal ratio combining (MRC). With the instantaneous SNR of the direct link from S to D_1 which is denoted by $\gamma_0 = P_1 |h_{s,1}|^2$, the mutual information of the transmission from S to D_1 can be expressed as follows

$$I_1 = \frac{2}{3} \log(1 + \gamma_0 + \gamma_1), \quad (20)$$

where the factor $\frac{2}{3}$ in (19) is due to the fact that three phases are used to transmit two new signals. Thus, the outage probability can be calculated as

$$\begin{aligned} P_{\text{out}}^{(\text{PS})} &= \Pr(I_1 < R_t) \\ &= \Pr\left(\frac{2}{3} \log(1 + \gamma_0 + \gamma_1) < R_t\right). \end{aligned} \quad (21)$$

Theorem 2: Given a target transmission rate R_t , the outage probability of the PSCMT protocol for the multiuser cooperative transmission system can be analytically calculated using (13), where[†] $R_0 = 2^{1.5R_t} - 1$, $a = \eta(\alpha_1 P_1 + \alpha_2 P_2) \theta_1$, $b = a P_2^{-1} (1 - \alpha_2)^{-1} + a \theta_1 \theta_2^{-1} P_1^{-1} (1 - \alpha_1)^{-1}$, $c = 1$.

It is desirable to obtain the optimal values of ρ and α which result in the lowest system outage probability (ρ for the TSCMT protocol and α for the PSCMT protocol, respectively). But it is intractable to derive the closed-form expressions for the optimal ρ and α due to the Bessel function and the integration involved in the explicit expression of $P_{\text{out}}^{(\text{TS})}$ and $P_{\text{out}}^{(\text{PS})}$, as shown in (13). However, for given

[†]The detailed derivation of the outage probability for the PSCMT protocol is omitted here because it follows the same steps which is given below Appendix A.

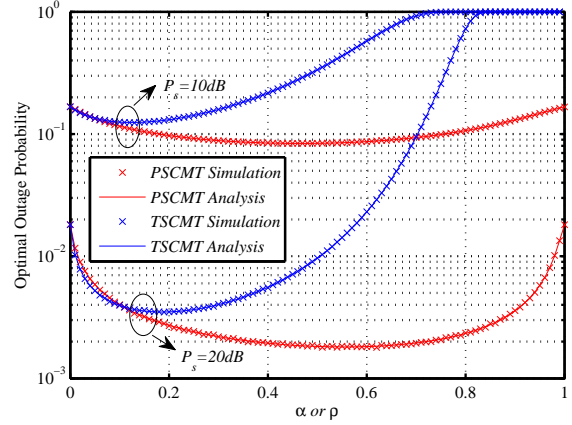


Fig. 5 Outage probability: numerical vs simulation. Other parameter: $d_{s,r} = 0.5$.

system configuration parameters, such as the source power and relay location, the optimization can be done offline by numerically evaluating optimal values of ρ and α .

5. Numerical Results

In this section, numerical results are provided to verify our theoretical analysis on the system outage probability of the two proposed protocols for the multiuser transmission system. Moreover, the effects of the source transmit power and relay position on the system outage performance will be discussed, based on which, the optimal values of ρ and α are numerically obtained.

Unless specifically stated, we set $R_t = 1 \text{ bit/sec/Hz}$, $\eta = 1$, $P_1 = P_2 = P_s$, and $m = 4$ (which corresponds to the urban areas and is widely adopted in literatures [27],[28]). Both $d_{s,1}$ and $d_{s,2}$ are normalized to 1. For simplicity, we set $\alpha_1 = \alpha_2 = \alpha$. The distance between D_1 and D_2 is normalized to 1, and R is placed on the height of the triangle composed of S , D_1 and D_2 , as illustrated in Fig. 4.

5.1 Verification of the Analytical Outage Probability

In this subsection, simulation results are obtained through the Monte Carlo simulation using (12) and (21) to check the accuracy of our analytical expressions for the outage probability in Theorem 1 and Theorem 2. As shown in Fig. 5, the simulation results closely match with the analytical results for all ρ of the TSCMT protocol, and for all α of the PSCMT protocol, which verifies the analytical expressions for the outage probability of the two proposed protocols.

It can also be obtained that, for the same transmit power P_s at S , the PSCMT protocol outperforms the TSCMT protocol in terms of optimal outage probability.

5.2 Effect of Source Power on Outage Probability

Fig. 6(a) shows the optimal outage probability against

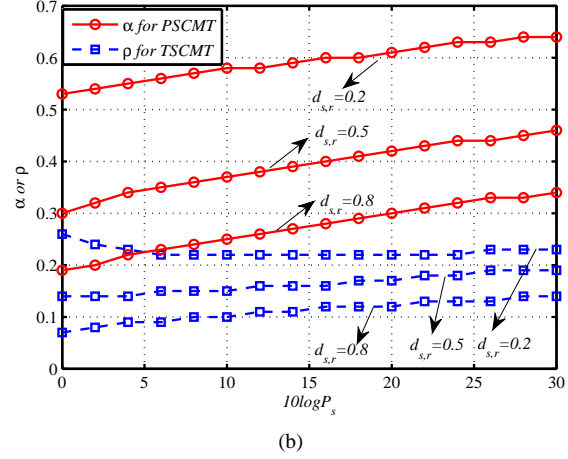
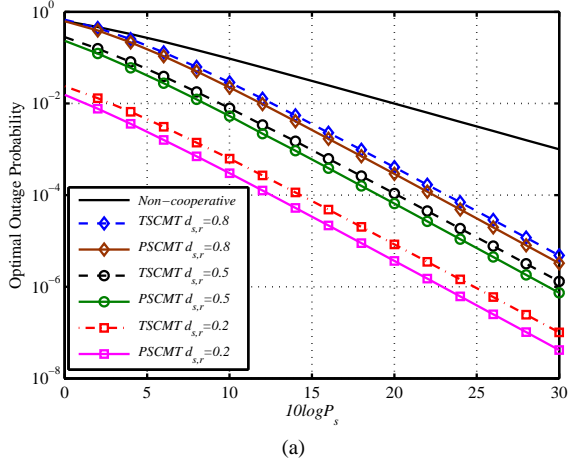


Fig. 6 (a) Optimal system outage probability against $10\log_{10}P_s$ (b) optimal α or ρ against $10\log_{10}P_s$.

$10\log_{10}P_s^{\dagger\dagger}$ of the two proposed protocols. We also compare the outage probability of the traditional non-cooperative scheme to the two proposed protocols. It can be seen that, the two proposed protocols are better than the traditional non-cooperative scheme to obtain lower outage probability. Moreover, in higher $10\log_{10}P_s$ region, as $10\log_{10}P_s$ increases, the outage probability of the TSCMT protocol and the PSCMT protocol decrease faster than the non-cooperative scheme. Besides, for the same $10\log_{10}P_s$, the PSCMT protocol outperforms the TSCMT protocol in terms of system outage probability in the whole $10\log_{10}P_s$ region.

Fig. 6(b) shows the optimal α (for the PSCMT protocol) and ρ (for the TSCMT protocol) versus $10\log_{10}P_s$. As shown in Fig. 6(b), the optimal α increases as $10\log_{10}P_s$ increases. This is due to the fact that, when the SNR is higher, the relay need less power to process information, thus more energy is left to be harvested.

5.3 Effect of Relay Location on Outage Probability

Fig. 7(a) shows the optimal outage probability versus $d_{s,r}$. As shown in Fig. 7(a), the optimal outage probability increases as $d_{s,r}$ increases, which indicates that to obtain lower outage probability, it is better to choose the relay near the source. For the relay with a particular $d_{s,r}$, the PSCMT protocol can always achieve lower system outage probability than the TSCMT protocol.

Fig. 7(b) shows the optimal α (for the PSCMT protocol) and ρ (for the TSCMT protocol) versus $d_{s,r}$. It can be observed that, the optimal α and ρ decrease as $d_{s,r}$ increases. This is due to the fact that, when the relay is far away from the source, it needs more power to correctly receive the information from the source, which makes less energy left to be harvested.

^{††}Because the variances of the noise at all terminals are normalized to 1, $10\log_{10}P_s$ actually denotes the signal-to-noise ratio (SNR).

6. Conclusion

In this paper, we investigated the multiuser transmission network with an EH cooperative relay. By adopting the time switching and the power splitting relay receiver architectures, we first proposed two cooperative protocols for the multiuser transmission system: the TSCMT protocol and the PSCMT protocol. Then, for each proposed protocol, we derived the explicit expression for the system outage probability. Moreover, we also discussed the effects of various system parameters, such as the source's transmit power and the relay location on the system outage performance. Numerical results showed that our proposed protocols achieve lower system outage probability without consuming additional energy compared with traditional non-cooperative scheme. Besides, for the same transmit power at the source, the PSCMT protocol is superior to the TSCMT protocol to obtain lower system outage probability.

7. Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

8. Acknowledgments

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Appendix A

This appendix derives the $P_{\text{out}}^{(\text{TS})}$ in (13) for the TSCMT protocol.

By denoting $|h_{r,1}|^2$ and $|h_{s,r}|^2$ as X and Y , we define the variable $Z = \frac{aXY}{bX+c} = \gamma_1$. We can see that Z is a combination of two independent random variables. Using the basic knowledge of the probability theory, we can obtain the cumulative density function (CDF) $F_Z(z)$ of Z which is given

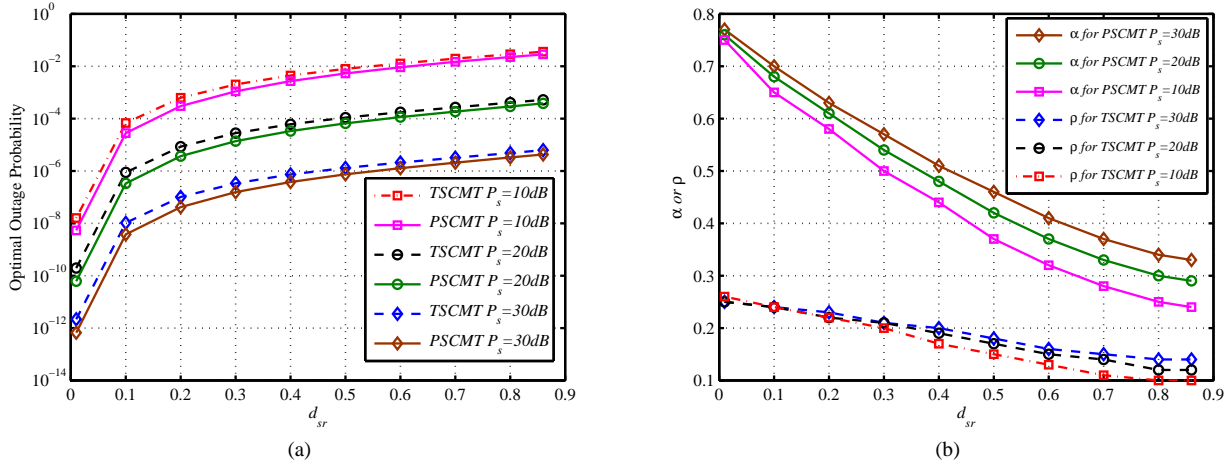


Fig. 7 (a) Optimal system outage probability against $d_{s,r}$ (b) optimal α or ρ against $d_{s,r}$.

by

$$F_Z(z) = 1 - \frac{\exp\left(-\frac{zb}{a\Omega_{s,r}}\right)}{\Omega_{r,1}} \sqrt{\frac{4zc\Omega_{r,1}}{a\Omega_{s,r}}} K_1\left(\sqrt{\frac{4zc}{a\Omega_{r,1}\Omega_{s,r}}}\right), \quad (\text{A} \cdot 1)$$

where $K_1(\cdot)$ denotes the first-order modified Bessel function of the second kind [29].

Since γ_0 is an exponentially distributed random variable with mean $P_1\Omega_{s,1}$, $P_{\text{out}}^{(\text{TS})}$ can be rewritten as follows

$$\begin{aligned} P_{\text{out}}^{(\text{TS})} &= \Pr(\gamma_0 + \gamma_1 < R_0) \\ &= \int_0^{R_0} \Pr[Z < R_0 - \tau] f_{\gamma_0}(\tau) d\tau \\ &= \int_0^{R_0} F_Z(R_0 - \tau) \frac{1}{P_1\Omega_{s,1}} \exp\left(-\frac{\tau}{P_1\Omega_{s,1}}\right) d\tau. \end{aligned} \quad (\text{A} \cdot 2)$$

The integral in (A-2) can't be directly calculated due to the $K_1(\cdot)$ in (A-1). By applying the series expansion of $K_1(\cdot)$ which is given in (A-3), we can rewrite $P_{\text{out}}^{(\text{TS})}$ in (A-4) as follows

$$\begin{aligned} K_1(x) &= \sum_{l=0}^{\infty} \frac{\left(\frac{x}{2}\right)^{2l+1}}{l!(l+1)!} \left(\ln \frac{x}{2} + C\right) \\ &\quad - \frac{1}{2} \sum_{l=1}^{\infty} \frac{\left(\frac{x}{2}\right)^{2l+1}}{l!(l+1)!} \left(\sum_{k=1}^l \frac{1}{k} + \sum_{k=1}^{l+1} \frac{1}{k}\right) + \frac{1}{x}, \end{aligned} \quad (\text{A} \cdot 3)$$

$$\begin{aligned} P_{\text{out}}^{(\text{TS})} &= \frac{1}{P_1\Omega_{s,1}} \left\{ \int_0^{R_0} \exp\left(-\frac{\tau}{P_1\Omega_{s,1}}\right) d\tau \right. \\ &\quad \left. - \int_0^{R_0} \frac{\exp\left(-\frac{(R_0-\tau)b}{a\Omega_{s,r}}\right)}{\Omega_{r,1}} \sum_{l=1}^{\infty} \frac{(R_0-\tau)^{l+1} \Omega_{r,1} c^{l+1}}{(a\Omega_{s,r}\Omega_{r,1})^{l+1} l!(l+1)!} \right. \\ &\quad \left. \times \left(\ln \frac{(R_0-\tau)c}{a\Omega_{s,r}\Omega_{r,1}} + 2C - \sum_{k=1}^l \frac{1}{k} - \sum_{k=1}^{l+1} \frac{1}{k}\right) \exp\left(-\frac{\tau}{P_1\Omega_{s,1}}\right) d\tau \right\} \end{aligned}$$

$$\begin{aligned} &- \int_0^{R_0} \frac{\exp\left(-\frac{(R_0-\tau)b}{a\Omega_{s,r}}\right) (R_0-\tau)}{a\Omega_{s,r}\Omega_{r,1} P_1\Omega_{s,1}} \left(\ln \frac{(R_0-\tau)c}{a\Omega_{s,r}\Omega_{r,1}} + 2C\right) \\ &\times \exp\left(-\frac{\tau}{P_1\Omega_{s,1}}\right) d\tau - \int_0^{R_0} \exp\left(\frac{(\tau-R_0)b}{a\Omega_{s,r}}\right) \exp\left(-\frac{\tau}{P_1\Omega_{s,1}}\right) d\tau \Big\}. \end{aligned} \quad (\text{A} \cdot 4)$$

By denoting the four integral items in the right hand side of the above equation as Q_1 , Q_2 , Q_3 and Q_4 respectively, we can obtain that

$$Q_1 = 1 - \exp\left(-\frac{R_0}{P_1\Omega_{s,1}}\right), \quad (\text{A} \cdot 5)$$

$$\begin{aligned} Q_2 &= - \sum_{l=1}^{\infty} \frac{\exp\left(-\frac{R_0 b}{a\Omega_{s,r}}\right) c^{l+1}}{P_1\Omega_{s,1} (a\Omega_{s,r}\Omega_{r,1})^{l+1} l!(l+1)!} \\ &\times \int_0^{R_0} \exp\left(-\frac{(a\Omega_{s,r} - bP_1\Omega_{s,1})\tau}{aP_1\Omega_{s,1}\Omega_{s,r}}\right) (R_0-\tau)^{l+1} \\ &\times \left\{ \left(\ln \frac{c}{a\Omega_{s,r}\Omega_{r,1}} + 2C - \sum_{k=1}^l \frac{1}{k} - \sum_{k=1}^{l+1} \frac{1}{k}\right) + \ln(R_0-\tau) \right\} d\tau \\ &= \sum_{l=1}^{\infty} \frac{\exp\left(-\frac{R_0 b}{a\Omega_{s,r}}\right) c^{l+1}}{P_1\Omega_{s,1} (a\Omega_{s,r}\Omega_{r,1})^{l+1} l!(l+1)!} \\ &\times \left\{ \left(\ln \frac{c}{a\Omega_{s,r}\Omega_{r,1}} + 2C - \sum_{k=1}^l \frac{1}{k} - \sum_{k=1}^{l+1} \frac{1}{k}\right) \right. \\ &\times \left(\frac{1}{P_1\Omega_{s,1}} - \frac{b}{a\Omega_{s,r}}\right)^{-l-2} \gamma\left(l+2, \frac{R_0}{P_1\Omega_{s,1}} - \frac{bR_0}{a\Omega_{s,r}}\right) \\ &\left. + \int_0^{R_0} \exp\left(\frac{(bP_1\Omega_{s,1} - a\Omega_{s,r})\tau}{aP_1\Omega_{s,1}\Omega_{s,r}}\right) \tau^{l+1} \ln \tau d\tau \right\}, \end{aligned} \quad (\text{A} \cdot 6)$$

where $\gamma(\cdot)$ denotes the incomplete gamma function. Q_3 can be rewritten as

$$Q_3 = \frac{\exp\left(-\frac{R_0}{P_1\Omega_{s,1}}\right) c}{a\Omega_{s,r}\Omega_{r,1} P_1\Omega_{s,1}} \left\{ \left(\ln \frac{c}{a\Omega_{s,r}\Omega_{r,1}} + 2C\right) \left(\frac{1}{P_1\Omega_{s,1}} - \frac{b}{a\Omega_{s,r}}\right)^{-2} \right.$$

$$\times \gamma \left(2, \frac{R_0}{P_1 \Omega_{s,1}} - \frac{bR_0}{a\Omega_{s,r}} \right) + \int_0^{R_0} \exp \left(\frac{(bP_1 \Omega_{s,1} - a\Omega_{s,r}) \tau}{aP_1 \Omega_{s,1} \Omega_{s,r}} \right) \times \tau \ln \tau d\tau \Bigg\}, \quad (\text{A} \cdot 7)$$

$$Q_4 = - \frac{a\Omega_{s,r}}{a\Omega_{s,r} - bP_1 \Omega_{s,1}} \times \left(\exp \left(\frac{R_0}{P_1 \Omega_{s,1}} - \frac{2R_0 b}{a\Omega_{s,r}} \right) - \exp \left(- \frac{R_0 b}{a\Omega_{s,r}} \right) \right). \quad (\text{A} \cdot 8)$$

Substituting (A·5), (A·6), (A·7) and (A·8) into (A·4), one can obtain the final expression of $P_{\text{out}}^{(\text{TS})}$, which is given in (13). This ends the proof for Theorem 1. \square

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